

## **COB-2023-1016 A COMPARATIVE STUDY BETWEEN THE COMBUSTION OF MINERAL COAL AND AÇAÍ SEED IN BOILERS BY MEANS OF THE CeSFaMB<sup>TM</sup>**

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**Abstract.** *The utilization of fossil fuels for energy generation has become popular since the beginning of the 17th century, as it increased emissions of harmful gases into the atmosphere from the burning of these fuels. Brazil is a rich country in natural resources and has considerable potential for investment in renewable energy, such as reusing agroforestry residues as energy biomass. Pará is Brazil's largest producer of açai, producing 1.4 million tons per year. About 70% of this fruit is composed of stone, often discarded irregularly in urban areas without a fitting end. The CeSFaMB<sup>TM</sup> is a comprehensive simulation of fluidized bed equipment providing accurate data at pilot and industrial scales, which can be used to simulate boilers operating wholly or partially with biofuels. This work aims to simulate the burning of mineral coal and açai stones in a Babcock & Wilcox bubbling fluidized bed boiler found in literature and, from this, to make an energy and emission comparison of the combustion gases of these fuels. Some results already analyzed in the laboratory showed that 1 kg of mineral coal corresponds to 1.66 kg of açai seed, making an energy balance of lower heating value. The seed has twice the content of volatiles than coal (78% and 36%, respectively), and the lower the moisture content of the samples of stone, the more the heating value (LHV) approaches the mineral coal. The comparative analysis will be done based on the temperature profile along the freeboard of the boiler in question, the percentage of emission of gases during combustion, such as CO, CO<sub>2</sub>, NO<sub>x</sub> and SO<sub>x</sub>, and the energy power of boiler operation açai stone and mineral coal. Thus, an analysis of the energy efficiency and gas emission of burning açai stone compared to mineral coal in the fluidized bed boiler, Babcock & Wilcox, taken from the literature. Finally, to give an energy purpose to a residue is considered an environmental liability in the state's regions, besides decreasing the production rate of greenhouse gases (GHG) from burning coal, producing green CO<sub>2</sub>, and generating carbon credits for industries.*

**Keywords:** *Mineral Coal, Açai Seed, Simulation, Boiler, CeSFaMB<sup>TM</sup>.*

### **1. INTRODUCTION**

The accelerated globalization has made the world's energy matrices obsolete in relation to the energy consumption required by human activities, thus the constant extraction and use of non-renewable energy sources has become common, consequently the damage caused to the environment. The world CO<sub>2</sub> emissions doubled in relation to the previous 30 years, which come mostly from the burning of fossil fuels as an energy source, which increases the production of harmful gases in the atmosphere, contributes to the greenhouse effect and accelerates global warming (Evans, 2021).

In Brazil, between the periods 2000 to 2020, fossil thermoelectric plants had an increase in the production of electricity from 30.6 TWh to 84.8 TWh, consequently the emissions of greenhouse gases (GHG) also increased in this sector totaling a 90% increase (IEMA, 2020). The excessive dumping of tons of carbon in the atmosphere deregulates the carbon cycle and accelerates the greenhouse effect, figure 1 shows the production of CO<sub>2</sub> in millions of tons per fossil fuel used in the thermoelectric sector, which can be seen that coal represents 17.4 million tons of CO<sub>2</sub> dumped into the earth's atmosphere by thermoelectric plants connected to the National Interconnected System.

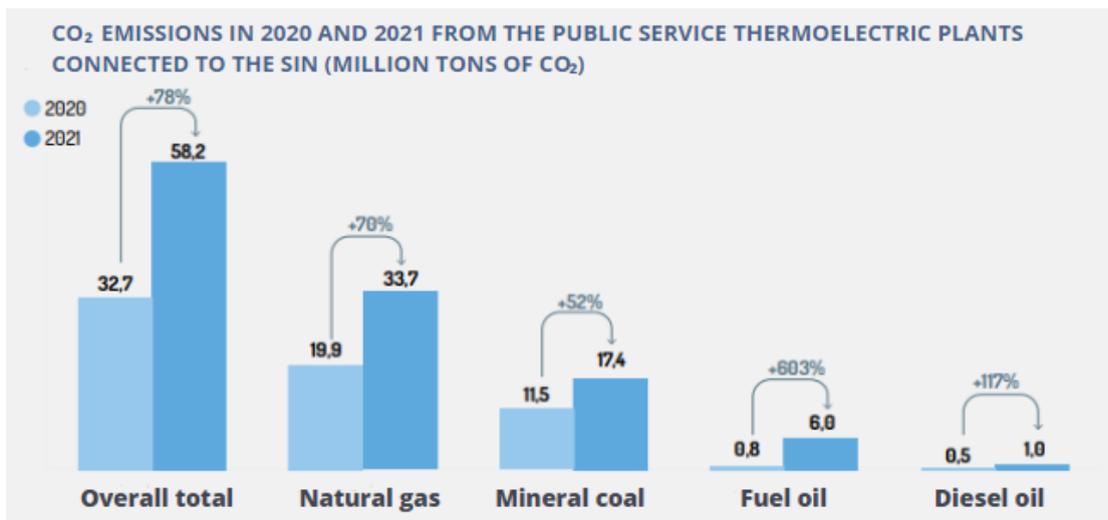


Figure 1. Increase in CO<sub>2</sub> emissions from fossil fuel combustion between 2020 and 2021.  
 Source: IEMA (adapted), 2020.

Brazil has about 79% of its internal energy matrix from renewable sources of energy, of which 8.8% of this installed capacity comes from biomass energy as a source of fuel (EPE, 2022). The national territory has a huge potential for energy production through biomass combustion, especially in regions near the Amazon forest or tropical forests, which have enormous potential for agroforestry waste that can be characterized and transformed into energy biomass.

According to Senai Cetiqt, in 2019, the state of Pará produced about 1.4 million tons of açai, and 70% of this production is composed of açai seed, demonstrating the enormous potential for waste generation, most of which is discarded in urban areas or does not have an adequate destination. Table 1 presents a survey conducted in the Jurunas neighborhood, in Belém, about the final destination of the açai seed from the pulp processing enterprises, which shows an overload of landfills managed by the State and the other half having inappropriate disposal (undetermined).

Table 1. Final destination of açai processing enterprises in Jurunas.

Entreprise	Frequency of collection	Initial disposal	Final disposal
E01	Daily collected	Alternative transportation	Undetermined
E02	3 times per week	Garbage truck	Landfill
E03	Daily collected	Alternative transportation	Undetermined
E04	Daily collected	Alternative transportation	Undetermined
E05	Daily collected	Alternative transportation	Undetermined
E06	3 times per week	Garbage truck	Landfill
E07	3 times per week	Garbage truck	Landfill
E08	3 times per week	Garbage truck	Landfill
E09	3 times per week	Garbage truck	Landfill
E10	3 times per week	Alternative transportation	Undetermined

Source: Negrão et al, 2021 (adapted).

With the large local supply of açai seed biomass resulting from the pulping at the processing sites, the implementation of this biomass as an energy source becomes an almost inexhaustible attraction in the region (Rendeiro et.al, 2008), in other words, an excellent alternative to be applied in reactor plants and industrial boilers as total or partial solid fuel.

The National Policy for Biofuels (RenovaBio), present in Brazil, already establishes the use of energy sources that favor the exchange of fossil fuels for biofuels, reduction of GHG and the production of excess CO<sub>2</sub> in the atmosphere. The use of açai seed as biofuel for boilers instead of mineral coal (fossil fuel) is an alternative that should be studied, but by deduction it shows to be viable because of the low amount of toxics and sulfur (due to be biodegradable), besides favoring the production of carbon credits for industries with thermoelectric plants and encourage the decarbonization of the atmosphere, consequently reducing the greenhouse effect.

This work aims to numerically compare the emissions of harmful gases, such as CO<sub>x</sub>, NO<sub>x</sub> and SO<sub>x</sub> and also greenhouse gases (GHG), and the freeboard temperature peaks by means of the CesFamB software. The analysis will use a Babcock & Wilcox bubbling fluidized bed boiler taken from the literature (Souza-Santos, 2010) and aims to obtain the behavior of harmful emissions and temperature profile of the freeboard by the different amounts of acai mixed with coal.

## 2. LITERATURE (BIBLIOGRAFIC) REVIEW

### BUBBLING FLUIDIZED BOILER

There are several known and currently used systems for converting heat into work, through a thermodynamic cycle. Among them, the most common is the steam cycle or Rankine cycle, which is used in equipment such as boilers and reactors (Çengel, 2013).

Among the numerous types of boilers and reactors, fluidized bed boilers (FBB) are perhaps the largest application among fluidized bed equipment around the world, which are about 10,000 boilers in operation. A fluidized bed boiler comprises a furnace and a convection heat exchange section. The furnace is made of a bubbling bed of incombustible solids and a free edge above it and the convective section is similar to any conventional boiler (Basu, 2006).

The large-scale development and commercialization of fluidized bed boilers (FBB) can be justified. For FBB systems, which use limestone for SO<sub>2</sub> removal, the amounts of limestone required are unknown and may be excessive. Experimental evidence to date shows that adequate control of sulfur emissions may require 2 to 5 times the theoretical amount of limestone. This represents an additional cost for the purchase of limestone, as well as costs associated with thermal losses and waste disposal. (Lange et al, 1978).

### COAL

One of the first energy sources used by man was coal, but it gradually lost space in the world energy matrix to oil and natural gas, because of the development of internal combustion machines. The interest in coal returned in the 1970s, because of the oil shock, and remains on the rise until today (Rohloff, 2017).

According to data from the Institute of Energy and Environment - IEMA (2020), the use of mineral coal by thermoelectric plants corresponds to 20% of fossil electricity production in Brazil, a production of about 10.8 TWh, which explains the enormous energy potential of this fossil fuel and allied to this the high emission of greenhouse gases.

Some literature presents data for characterization of coal and charcoal, and the percentages of Volatile Matter (VM), Ash, High Heating Value (HHV), Fixed Carbon (FC), Carbon (C) and Sulfur (S) found during the characterization of coal and charcoal show the production of elements that react during combustion to form other elements considered harmful to the earth's atmosphere (compounds of CO<sub>x</sub>, SO<sub>x</sub> and others), as shown in Table 2.

Table 2. Proximate analysis, ultimate analysis and HHV (MJ/kg) of literature coal samples.

	Proximate Analysis				Ultimate Analysis				
	VM (%)	Ash (%)	FC (%)	HHV (MJ/kg)	C (%)	H (%)	O (%)	N (%)	S (%)
Souza-Santos (2010)	38.0	9.40	47.60	30.84	73.20	5.10	7.90	0.9	3.0
Colombian Coal - Rohloff (2017)	37.75	9.89	52.36	28.20	69.77	5.03	13.19	1.49	0.64
Brazilian Coal - Rohloff (2017)	27.80	33.73	38.47	20.60	50.80	3.77	9.86	0.93	0.91
Charcoal - Rohloff (2017)	26.63	16.84	56.53	23.70	64.13	2.40	15.20	1.23	0.20

**AÇAÍ SEED**

Açaí is a typical fruit of the northern region of Brazil and the country stands out as the largest producer, consumer and exporter of this product. The most common açazeiro is the species Euterpe Oleracea, a palm tree with strains typical of the state of Pará, the largest national producer (Senai Cetiqt, 2019).

During the processing of the açai fruit, the pulp presents the greatest relevance in the production chain, which is consumed and marketed for export. However, because it accounts for only 30% of the fruit, a problem arises of the generation of waste of açai seed with no purpose, mainly because the commercialization of the fruit pulp comes from the processing done by large industries (Senai Cetiqt, 2019). Figure 2 below shows the processing chain of the fruit and generation of the percentages of the products resulting from this production.

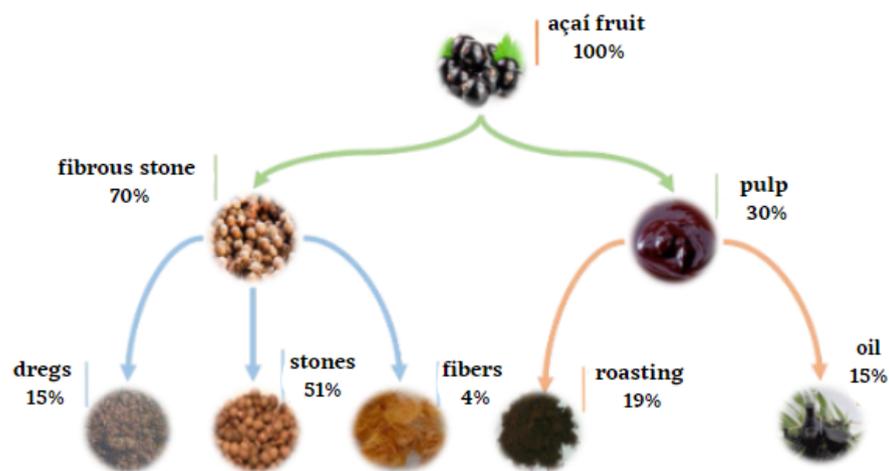


Figure 2. Waste and products generated.  
 Source: Senai Cetiqt, 2019 (adapted).

The biomass of açai seed has great potential to be used in thermal processes for bioenergy generation, because it presents advantages from the environmental, social and economic point of view. The study of the physical-chemical properties of the stone allows the use of this waste considered an environmental liability in energy production through processes such as combustion. (Oliveira, 2021)

Table 5 presents the characterization of the açai seed from different literatures, which present significant percentages of Volatile Matter (VM), Carbon (C), resulting in good percentages of High Heating Value (HHV). Moreover, the non-significant percentages of Nitrogen (N) and Sulfur (S) help to reduce the production of harmful (NO<sub>x</sub> compounds, SO<sub>x</sub> and others) to the earth's atmosphere and greenhouse gases.

Table 3. Proximate analysis, ultimate analysis and HHV (MJ/kg) of the literature of açai samples.

	Proximate Analysis				Ultimate Analysis				
	VM (%)	Ash (%)	FC (%)	HHV (MJ/kg)	C (%)	H (%)	O (%)	N (%)	S (%)
Seye et al. (2008)	80.35	1.15	18.50	16.36	47.80	5.57	45.48	0.0	0.0
Santos (2011)	79.93	1.39	18.68	18.14	46.04	6.77	37.73	7.99	0.08
Oliveira (2021) - average value	63.00	1.00	26.00	19.75	46.72	5.18	46.42	0.68	0.0
Rendeiro and Nogueira (2008)	79.40	1.10	19.50	19.16	46.00	6.00	46.10	0.80	0.0

Source: Ferreira et al., 2022 (adapted).

### 3. METHODOLOGY

This paper aims to show a comparative study of energy and emissivity between the burning of coal and acai seed, using data found in the literature on energy characterization of these fuels. Based on these premises, we used a comprehensive simulator of bubbling and circulating fluidized bed equipment, the Comprehensive Simulator of Fluidized and Moving Bed Equipment (CeSFaMB™), which is able to accurately reproduce data from large scale industrial units for combustion or gasification tests of various types of fuels and gases.

With the equipment library provided within the CeSFaMB™ folders, a ".dat" of a Babcock & Wilcox bubbling fluidized bed boiler was used. In addition, parameters such as type of equipment, minimum and maximum conversion of fixed carbon in the bed, convergence criteria for the numerical integration of mass and energy, model of the minimum fluidization velocity of the gas that is injected into the bed, and model of the size of the bubbles passing through the bed were set standard for all simulations, as shown in Table 4.

Table 4. Parameters standardized across all simulations.

Parameters	Percent/Model/Others
Guessed minimum % conversion of fixed-carbon in the bed (CCMAXP)	90%
Guessed maximum % conversion of fixed-carbon in the bed (CCMINP)	99%
Convergence criterion for the numerical integration of mass and energy (TLOMB)	1*D-06
Operating model (IGASF)	Boiler or furnace
Equipment type (IEQUIP)	Bubbling fluidized bed
Minimal velocity model (MUMF)	Model by Babu (MUMF = 1)
Buble model (MBUB)	Model by Horio & Nonaka (MBUB = 2)

The values shown in Table 5 for proximate analysis, elemental analysis and higher calorific value requested during the simulations were taken from the literature by Souza-Santos (2010) for charcoal and Rendeiro et. al (2008) for açai seeds.

Table 5. Proximate analysis, ultimate analysis and HHV (MJ/kg) of the fuels used in the simulation.

	Proximate Analysis				Ultimate Analysis				
	VM (%)	Ash (%)	FC (%)	HHV (MJ/kg)	C (%)	H (%)	O (%)	N (%)	S (%)
Açai Seed (Rendeiro et. al, 2008)	79.40	1.10	19.50	19.16	46.00	6.00	46.10	0.80	0.0
Mineral coal (Souza-Santos, 2010)	38.00	9.40	47.60	30.84	73.20	5.10	7.90	0.90	3.0

Equation 1 for boiler power was adapted and with equation 2 the mass flow rates of the fuel inputs were determined for each simulation, for engineering data and quick handling of units this equation is sufficient. The operating power of the boiler used in the example was 1.65 MW, but with the data from the higher calorific value of the fuels and the mass flow rate of the coal fuel provided in the example, an approximate value for operating power of 1.54 MW was calculated. Thus, the input mass flow rates of each fuel with partial or full biomass operation were stipulated, as shown in Table 3.



Finally, figure 4 shows the simulation strategy of all the runs, which followed the block diagram proposed by Souza-Santos (2010).

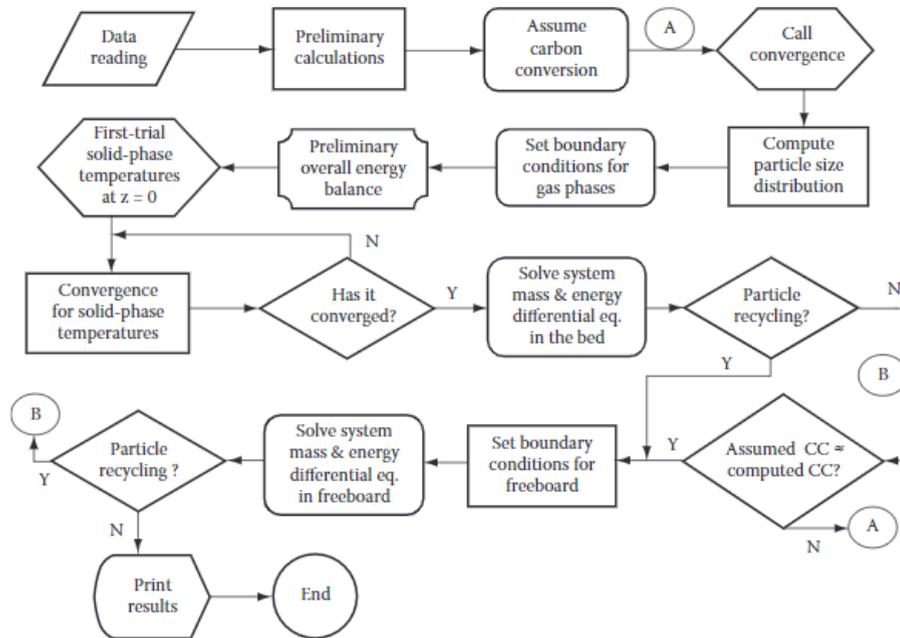


Figure 4. Simplified block diagram showing the simulation strategy.  
Source: Souza-Santos, 2010.

#### 4. RESULTS AND DISCUSSION

With the results of the simulations, the emissions of harmful and greenhouse gases during the input simulations were verified, that is, mass percentages of O<sub>2</sub>, SO<sub>2</sub>, NO and CO<sub>x</sub> compounds were extracted. Table 7 shows all the data taken from the CesFaMB™ results.

Table 7. Percentages of gas emissions during combustion.

Input reason	Mass percentage of O <sub>2</sub> (%)	Mass percentage of NO (%)	Mass percentage of CO (%)	Mass percentage of SO <sub>2</sub> (%)	Mass percentage of CO <sub>2</sub> (%)
80% coal 20% açaí seed	9.3713	0.1142	0.1272	0.0744	15.402
70% coal 30% açaí seed	8.8755	0.1131	0.0512	0.0900	15.9427
50% coal 50% açaí seed	8.2146	0.1267	0.0127	0.1001	16.6062
100% açaí seed	9.6686	0.1383	0.0799	0	15.4075
100% coal	8.5478	0.0978	0.1125	0.0978	16.1622

The higher O<sub>2</sub> release in the 100% açai seed simulation can be explained due to the high percentage of the oxygen element in the ultimate analysis. On the other hand, CO<sub>2</sub> production ends up being low due to the low rate of carbon in this same analysis for the açai seed. Although the 50-50% açai seed/coal simulation obtains the highest amount of CO<sub>2</sub>, the generation of carbon dioxide from these seeds is partially green (removed from the surface and returned in normal quantities), and the other part removed from the subsoils exceeding the amount of the element in the atmosphere, thus, part of this production generates less excess CO<sub>2</sub> contributing to the ONU decarbonization goals by 2030. On the other hand, the 100% coal simulation generates 16.16% of final emissions entirely from underground, interfering with the carbon cycle and accelerating the greenhouse effect.

Another essential piece of information in the 100% coal simulation was the identification of the highest emissions of CO, a highly harmful gas to the Earth's atmosphere, which in addition to being toxic, can react spontaneously with terrestrial oxygen and generates more CO<sub>2</sub> in the atmosphere. In addition, the production of sulfur dioxide, another highly toxic gas was identified in greater quantity in the simulations of 50-50% açai seed/coal and 100% coal, but the 50-50% can be explained due to the reaction of the high oxygen content of the açai seed ultimately with the sulfur content of the coal foremost, which does not occur in 100% coal, presenting another negative fact to using only mineral coal. Finally, in the 100% açai wheels, SO<sub>2</sub> is not produced due to the açai ultimate containing zero percentage of sulfur and despite having 15.40% of CO<sub>2</sub> mass emission, it is a CO<sub>2</sub> considered green, removed from the surface is injected again, not interfering with the carbon cycle in the Earth's atmosphere.

The temperature profile of the freeboard during the burning of the fuels was also verified, so it was possible to analyze the temperature peaks of the flue gases inside the boiler according to the inputs inserted. Figures 5, 6 and 7 show the behavior of the gases during the increase of the freeboard geometry height.

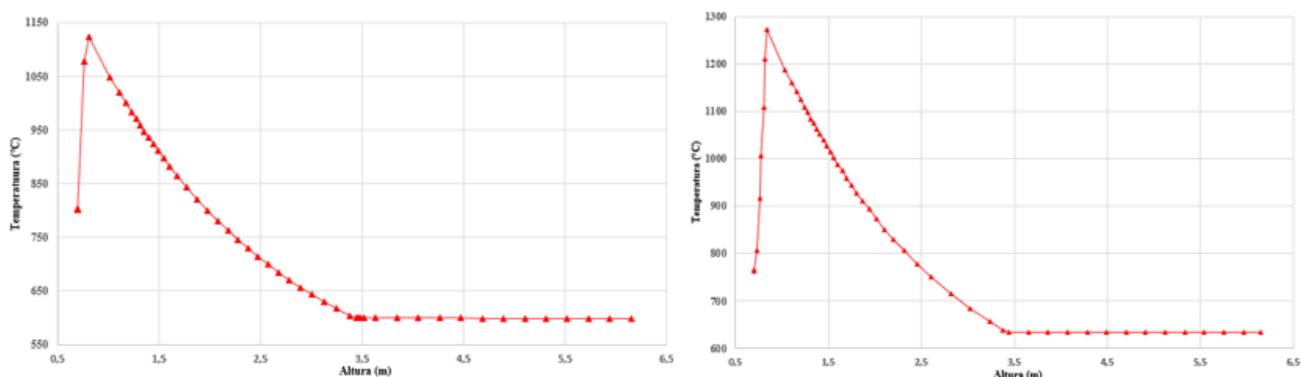


Figure 5. Temperature x freeboard height curves for 20-80% and 30-70% açai/coal inputs.

In Figure 5, it can be seen that the temperature peaks of the flue gases in the lowest section of the freeboard (0.7 meters), 1122.8 °C for 20-80% and 1272.2 °C for 30-70%, is the result of the burning of the volatile gases of the fuels and the oxygen content present in the elemental of the açai seed, which generates a higher peak temperature in this section as its mass flow rate is increased. In addition, it can be verified the constant drop in temperature after this peak due to the reaction of the combustion gases reaching the end is reduced as it reaches the highest height of the freeboard (2.38 meters).

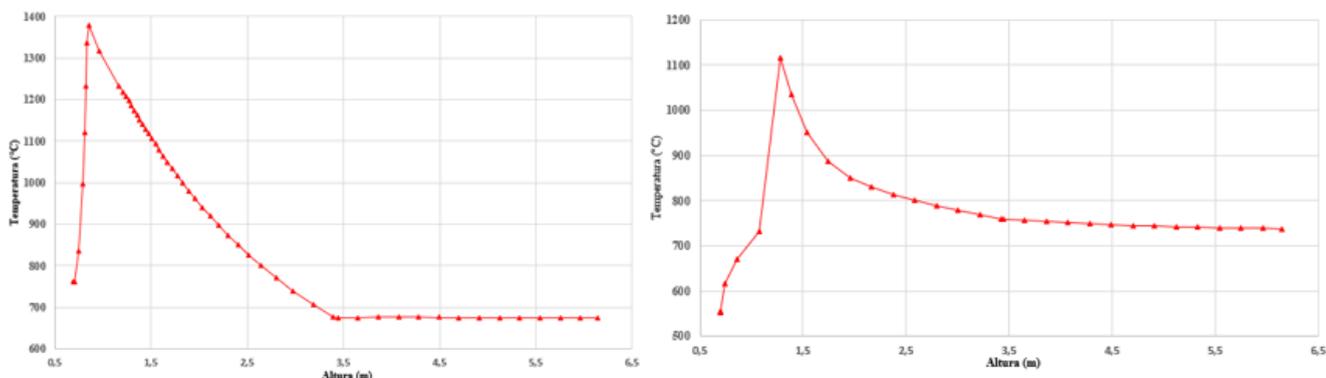


Figure 6. Temperature x freeboard height curves for 50/50% and 100% açai inputs.

Figure 6 shows the temperature peaks at the beginning of the freeboard section (0.7 meters) due to volatiles and oxygen release during fuel burning, 1380 °C for 50-50% and 1116. 2 °C for 100% açai. However, it can be observed that the temperature variation from the peak to the maximum height point of the freeboard is lower than concerning the 50-50% açai/coal, due to the amount of energy released during the burning of açai stone, as it has a high oxygen content favoring high temperatures of the gases released during combustion. In addition, burning 100% açai requires greater mass input flow than mineral coal but does not generate sulfur dioxide (SO<sub>2</sub>) products, and the CO<sub>2</sub> product developed is considered green.

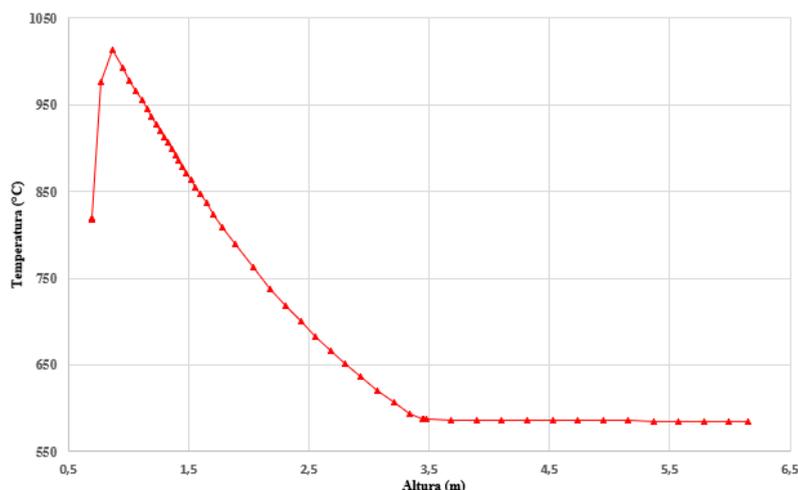


Figure 7 - Temperature x freeboard height curve for 100% coal input.

100% açai due to its lower amount of volatile matter (difference of 41.4%). In addition, the burning of 100% açai requires a higher mass input flow than coal but does not generate sulfur dioxide products (SO<sub>2</sub>), and in addition, the CO<sub>2</sub> generated is considered green. It does not interfere with the excess carbon cycle (as in coal burning) since only CO<sub>2</sub> from the surface is used, and the process works with tolerable amounts already present in the atmosphere.

## 5. CONCLUSION

Açai is a fruit popularized throughout Brazil, especially in the country's northern region, but inadequate disposal of its post-processing stone is a problem that needs solutions. Assigning an energy purpose to this agroforestry residue and generating carbon credits for industries and the like also ensures the production of green carbon dioxide, which does not abruptly interfere with the carbon cycle. Therefore, estimating some parameters of its combustion before the actual burning is fundamental to understanding the energy functioning of a boiler operating totally or partially with this biomass.

The temperature profile data from the firing inputs demonstrate that the açai seed can be substituted energetically for mineral coal. This analysis can be made in comparison to the peaks of the temperature profiles and final temperature along the boiler freeboard according to the inputs entered in CesFaMB™, especially if it replaces mineral coal with açai seed (a difference of 83°C from peak to peak and 94°C of temperature at the maximum height of the freeboard). However, its differential is in the emission of harmful gases and the greenhouse effect, since CO<sub>2</sub> generation can be considered green because it does not abruptly interfere with the carbon cycle, using only carbon already found on the earth's surface, which avoids the acceleration of the greenhouse effect and generates carbon credits for industries that use thermoelectric plants. In addition, the production of SO<sub>2</sub> is null in the burning of açai kernel since it does not have a percentage of sulfur in its elemental analysis composition, so it does not generate SO<sub>x</sub> products.

Concerning energy parameters, the best behaviors were those of the partial replacement of coal by açai seed (input 20-80%, 30-70%, and 50-50% coal/açai seed), since the highest temperature peaks found along the freeboard were in these simulations, 1122.8 °C, 1272.2 °C, and 1380°C, respectively. In addition, the açai seed, from a residue considered an environmental liability, now has an energy purpose and contributes to the generation of smaller amounts of greenhouse gases and harmful gases to the atmosphere. Finally, the development of new technologies for global decarbonization is necessary. The present study not only presents an alternative to the goal of reducing carbon production described by the ONU by 2030 but also generates carbon credits for industries at pilot and industrial levels.

## 6. ACKNOWLEDGEMENTS

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